Journal of Forestry Research (2013) 24(2): 317−324
DOI 10.1007/s11676-013-0355-8

ORIGINAL PAPER

Analysis of soil moisture variation by forest cover structure in lower western Himalayas, India

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Received: 2012-01-20; Accepted: 2012-11-18

Abstract: Soil moisture affects various hydrological processes, including evapotranspiration, infiltration, and runoff. Forested areas in the lower western Himalaya in India constitute the headwater catchments for many hill streams and have experienced degradation in forest cover due to grazing, deforestation and other human activities. This change in forest cover is likely to alter the soil moisture regime and, consequently, flow regimes in streams. The effect of change in forest cover on soil moisture regimes of this dry region has not been studied through long term field observations. We monitored soil matric potentials in two small watersheds in the lower western Himalaya of India. The watersheds consisted of homogeneous land covers of moderately dense oak forest and moderately degraded mixed oak forest. Observations were recorded at three sites at three depths in each watershed at fortnightly intervals for a period of three years. The soil moisture contents derived from soil potential measurements were analyzed to understand the spatial, temporal and profile variations under the two structures of forest cover. The analysis revealed large variations in soil moisture storage at different sites and depths and also during different seasons in each watershed. Mean soil moisture storage during monsoon, winter and summer seasons was higher under dense forest than under degraded forest. Highest soil moisture content occurred at shallow soil profiles, decreasing with depth in both watersheds. A high positive correlation was found between tree density and soil moisture content. Mean soil moisture content over the entire study period was higher under dense forest than under degraded forest. This indicated a potential for soil water storage under well managed oak forest. Because soil water storage is vital for sustenance of low flows, attention is needed on the management of oak forests in the Himalayan region.

Keywords: soil moisture; oak forest; soil matric potential; tree density; degraded forest

Introduction

Soil moisture is widely recognized as a key variable in studies related to environment, meteorology, hydrology, agriculture and climate change. From a hydrological viewpoint, soil moisture content controls the partitioning of rainfall into runoff and infiltration and therefore affects runoff, erosion, solute transport, and land-atmosphere interactions, as well as range of geographic and pedogenic processes in catchments (Aubert et al. 2003). The role of soil moisture in hydrological processes has been extensively studied over recent decades at catchment scale and has received increasing attention from the hydrological scientific community. However, soil moisture is one of the most difficult variables to estimate because of its interaction with factors such as vegetation, soil, and topography (Venkatesh et al. 2011). The estimation of soil moisture regimes has to deal with the probability of several conditions of the soil moisture status in an average year, and therefore has to be based on long observation periods.

Soil moisture on a catchment scale exhibits a high degree of variability in space and time and is influenced by a number of factors, such as topography (Wilson et al. 2005; Moore et al. 1988; Western et al. 1999), soil properties (Bell et al. 1980), land cover/vegetation (Mahmood and Hubbard 2007; Fu and Chen 2000), precipitation and other microclimatic conditions (Famiglietti et al. 1998). Researchers have addressed soil moisture variability by evaluating the factors controlling soil moisture, determining the significance in ecosystem processes and predicting soil moisture in catchments or at large scales (Anderson and Kneale 1980; Bárdossy and Lehmann 1998; Zhao et al. 1999). Little attention is paid, however, to the influence of land use on soil moisture (Fu et al. 2003). Assessing the effects of land use

Fund project: Impact assessment of land use on hydrologic regime in selected micro-watersheds in lesser Himalayas, Uttarakhand, India

The online version is available at http:// www.springerlink.com

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on soil moisture through modeling is a complicated task because differences in land uses produce change in soil properties and evapotranspiration (Andrew et al. 1998). Since land-use changes directly affect the soil moisture regime and, consequently, the hydrological behaviour of a watershed, *in situ* measurements of spatial and temporal variation in soil moisture under varying land cover types are crucial in hydrological studies.

In India, the forested areas in the lower western Himalayan ranges comprise the headwater catchments for many hill streams that are major sources of water supply in hilly regions. These streams also form important tributaries of major rivers in north India. However, these head water catchments have experienced severe degradation in forest cover due to grazing, deforestation and other human activities. This change in forest cover is likely to alter the soil moisture regime and consequently, the flow regime in the streams. However, the effect of change in forest cover on soil moisture regimes of this hydro-ecologically sensitive region has not been studied through long term field observations. A better understanding of the soil moisture variability under changing land cover is important for regulation of stream flows and erosion control. Soil moisture measurements are also useful for improving both the predictive capability of runoff models and the validation of hydrological process representations. The objective of our study was to monitor soil moisture in the field under varying forest cover conditions on a long term basis and to analyse and understand the temporal and spatial variation in soil moisture storage under these land cover types. We undertook field monitoring and investigation in two forested watersheds having different forest cover types in the lower Himalayan range in Uttarakhand state, India.

Materials and methods

Study area

We studied two small watersheds, Arnigad (30°26′13.9″ N, 78°05′37.4″ E) and Bansigad (30°27′9.1″ N, 78°02′45.9″ E), located 36 km north of Dehradun near Mussoorie (situated on the first mountain ridge beyond Dehradun) in Uttarakhand state of India (Fig. 1). Arnigad watershed covers 285.7 ha and supports moderately dense oak forest with land use of 83% forest, 12% habitation and 5% barren land. Bansigad watershed covers 190.5 ha and supports moderately degraded oak forest with areal coverage of 65% forest, 5% habitation, 28% barren, and 2% agriculture. Elevations at Arnigad and Bansigad range from 2,220 to 1,640 m above m.s.l. and 2,160 to 1,620 m above m.s.l., respectively. The mean orientation of both watersheds is south. The drainage pattern of both watersheds is of the dendritic type. Annual rainfall in mussoorie is about 2005 mm of which 60%–85% is received during monsoon season (June to September) (Hanner 2006). In Mussoorie, mean annual air temperature is 13.7 °C. The hottest month is June with an average (1961–1995) air temperature of 19.8 °C, and the coldest month is January with an average air temperature of 6 °C (Hanner 2006). The Mussoorie range, constituting the Proterozoic to Lower Cambrian rocks of the Lesser Himalaya is separated from the Cainozoic Siwalik Group and the Dun gravels by the MBT (Thakur and Pandey 2004), that is a north–northeast dipping thrust along which the Lesser Himalayan rocks are thrust over the Siwaliks (Rautela et al. 2010). The main parent material in this area consists of quartzite, schist, slates, phyllite, hard sandstones, limestone and dolomite (Bartarya 1995).

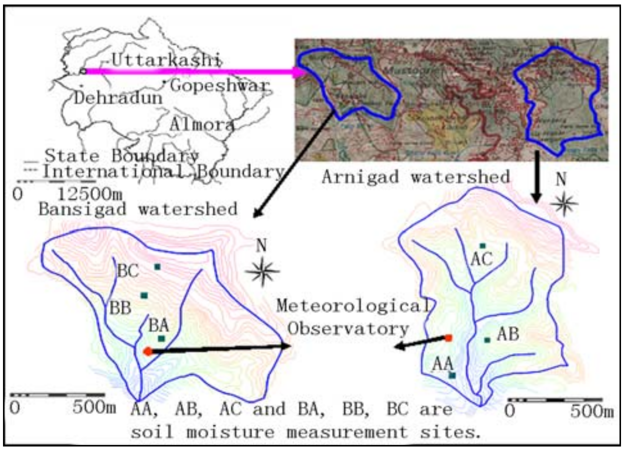

Fig. 1 Location map of Arnigad and Bansigad watersheds

Data collection

Data on soil moisture and rainfall were collected during June 2008 to May 2011 in each watershed. Data were also collected on soil properties and vegetation characteristics. The methods and techniques of data collection are described below.

Soil moisture data

Soil moisture levels can be expressed in terms of soil water content or soil matric potential. In the present study, Soil matric potential was measured using electrical resistance probes of 'Water Mark' make that operate on the principle that the electrical resistance of the probe is proportional to its moisture content. Two electrodes are embedded inside the probe with a cable extending to the surface. The probes are buried in the soil at desired depth of measurement. The water moves in and out of the probes in equilibrium with the moisture content in the surrounding soil. The resistance is measured between the two electrodes by attaching a portable meter to the cable. The measurement is related to soil water potential.

Three sites representing topographic highs and lows were established in each watershed for measuring the soil potential (Fig. 1). The probes at each site were installed at 0.25 m, 0.50 m and 0.80 m depths respectively to monitor the soil moisture at different root zone depths. A hand held read-out unit, when connected to probes, provided the soil matric potential (kPa). The soil matric potential in all the sensors was monitored at fortnightly intervals. While installing the probes, undisturbed soil samples were collected from all three depths at each point in each watershed and soil moisture retention curves were developed for each

of the soil samples in laboratory using pressure plate apparatus for the pressures 1, 33, 50, 70, 100, 300, 500, 700, 1000, and 1500 kPa. The soil moisture retention curves of Arnigad (Fig. 2) and Bansigad (Fig. 3) watersheds were used to convert the observed soil matric potential values of respective sampling points to equivalent values of volumetric soil moisture content. As an example, the volumetric soil moisture content at few selected pressures for all the sites is shown in Table 1. In order to assess the response of soil moisture to rainfall, daily rainfall was also recorded using an ordinary rain gauge that was installed in the meteorological observatory of each watershed.

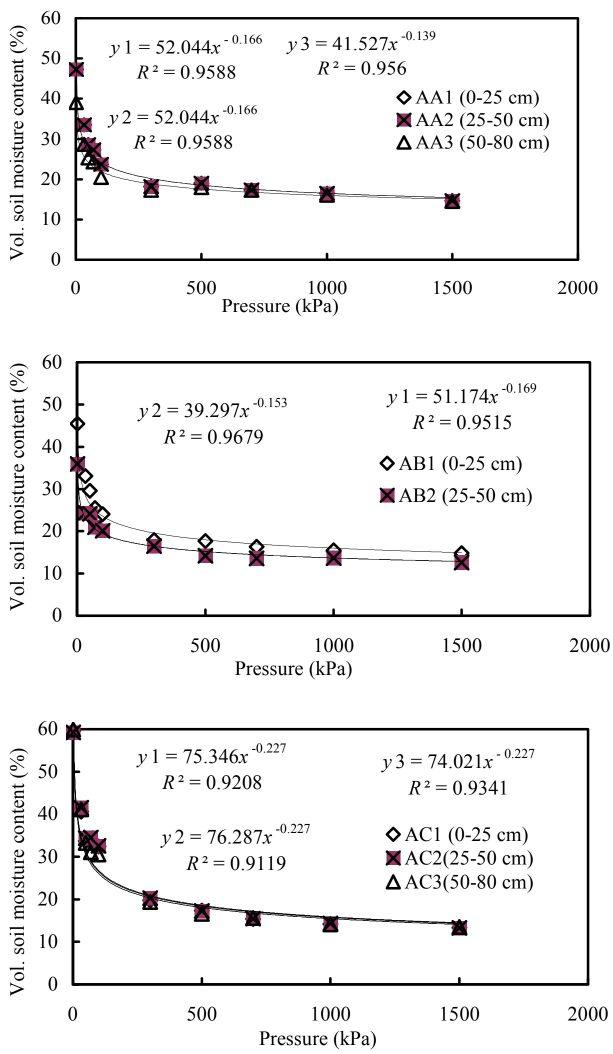

Fig. 2 Soil moisture retention curves of Arnigad watershed

Soil physical data

In order to understand soil moisture variation in relation to soil physical properties, soil samples were collected from five depths at each of the soil moisture monitoring sites in both watersheds. These samples were analyzed in the laboratory for particle size distribution, bulk density, soil organic carbon and organic matter content. The particle size analysis was carried out using the sieve method and the ‘Particle Size Analyzer’ for determination of the fraction of coarse and finer particles respectively. The soil texture was determined as per USDA classification. In Arnigad watershed, the soil properties were found to vary along the depth, but these varied little in spatial scale. Similar observations were also made from soil sample analysis of Bansigad watershed. For presentation purpose and to give the reader a general idea of the soil properties, average value of soil properties was computed at each depth from the distributed values of three moisture monitoring sites. The computed average values of various soil properties in Arnigad and Bansigad watersheds are presented in Table 2.

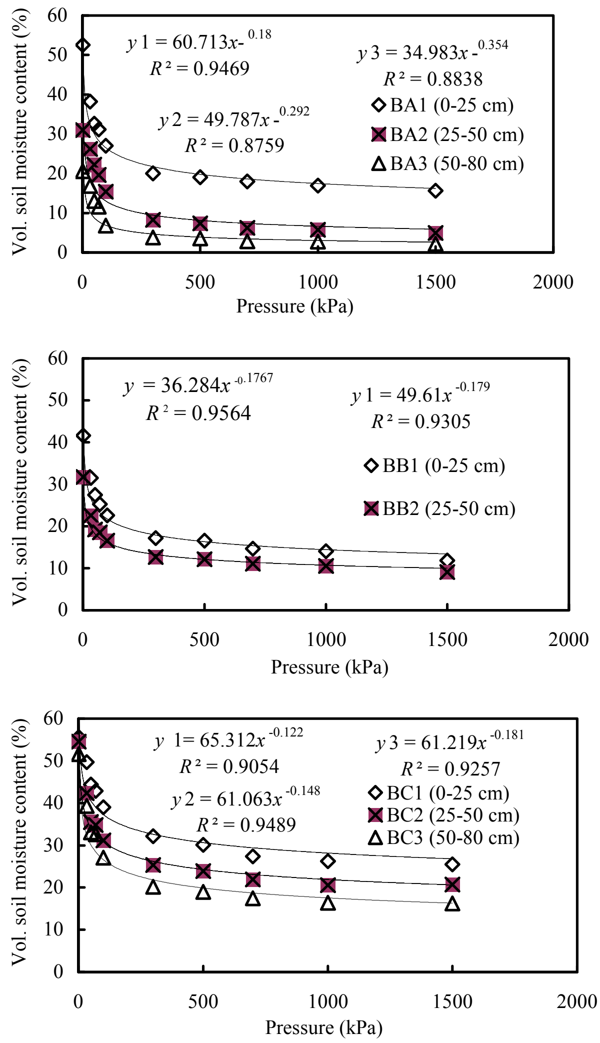

Fig. 3 Soil moisture retention curves of Bansigad watershed

Vegetation data

Vegetation survey was carried out at all three moisture measuring sites in each watershed. Five quadrants of 10 m×10 m size were laid out at each site. Species composition of the forests in Arnigad watershed consisted of 98% of oak trees and 2% others. The Bansigad watershed consisted of 64% of Oak trees, 17% of Cupressus, and 19% of others. The diameter at breast height (dbh) was measured at 1.73 m height. The survey indicated a large variation in tree density and dbh values at different sites (Table 3)

in both watersheds. As can be observed from Table 3, the average dbh and tree density in Arnigad watershed were higher by about 98% and 28% respectively than in Bansigad watershed.

Table 1. Volumetric soil water content at different sites in the study watersheds

Name of watershed	Site code	Depth (cm)	Volumetric soil water (%) at different pressures		
			1 kPa	33 kPa	1500 kPa
Arnigad	AA1	0-25	47.31	33.54	14.69
	AA2	25-50	47.31	33.54	14.69
(Dense	AA3	50-80	39.04	28.68	14.45
Oak	AB1	0-25	45.42	33.09	14.79
forest)	AB2	25-50	35.99	24.36	12.61
	AC1	0-25	59.65	40.60	13.37
	AC2	25-50	59.26	41.53	13.23
	AC3	50-80	59.90	41.18	13.49
	Average		49.24	34.56	13.91
Bansigad	BA1	0-25	52.51	38.17	15.64
(Degraded	BA2	25-50	30.95	26.20	4.91
mixed	BA3	50-80	20.59	16.86	2.17
forest)	BB1	0-25	41.60	31.50	11.82
	BB2	25-50	31.77	22.63	9.12
	BC1	0-25	55.58	49.69	25.48
	BC2	25-50	54.57	42.32	20.70
	BC3	50-80	51.55	39.31	16.21
	Average		42.39	33.33	13.25

Data analysis

There is no any single point in a watershed that represents the soil moisture of the watershed as a whole. It is obvious that measurements from many points inside each watershed must be averaged to study the variation in soil moisture among watersheds and land uses (Konstantin et al. 1996).

In the present study, we computed a number of variables of mean soil moisture content from the observed soil moisture data. Let soil moisture content of site i, layer j and sampling occasion k be expressed as $M_{i,j,k}$ and let N_p be the number of sites, N_l the number of sampling layers or depths and N_t the number of sampling occasions. The variables of mean soil moisture were computed for monthly as well as for entire period of observation using the equations proposed by Qiu et al. (2001).

(i) Time-averaged soil moisture content at site i, and at layer j ($M_{i,j}$).

$$M_{ij} = \frac{1}{N}\sum_{k=1}^{N_t} M_{ijk} \tag{1}$$

(ii) Mean soil moisture content of site i (M_i)

$$M_i = \frac{1}{N_l N_t}\sum_{j=1}^{N_l}\sum_{k=1}^{N_t} M_{ijk} \tag{2}$$

(iii) Mean soil moisture content at soil layer j (M_j)

$$M_j = \frac{1}{N_p N_t}\sum_{i=1}^{N_p}\sum_{t=1}^{N_t} M_{ijk} \tag{3}$$

Table 2. Soil physical properties of study watersheds

Depth (cm)	Soil organic carbon (%)	Organic matter (%)	B. D. ($g \cdot cc^{-1}$)	Sand (%)	Silt (%)	Clay (%)	Soil texture
Arnigad watershed (Dense Oak forest)							
0 - 15	3.31	5.71	1.01	67.75	14.00	18.51	Sandy Loam
15 - 30	2.30	3.97	1.05	66.07	13.33	20.51	Sandy Loam
30 - 60	2.51	4.33	1.08	67.40	14.67	17.83	Sandy Loam
60 - 90	2.41	4.16	1.11	69.17	12.67	18.83	Sandy Loam
90 - 120	1.54	2.65	1.16	67.50	13.00	19.40	Sandy Loam
Bansigad watershed (Degraded mixed forest)							
0 - 15	2.37	4.09	1.06	74.27	11.33	14.40	Sandy Loam
15 - 30	1.91	3.29	1.09	72.93	11.33	15.83	Sandy Loam
30 - 60	2.07	3.57	1.15	67.80	14.33	15.17	Sandy Loam
60 - 90	1.67	2.87	1.18	73.80	11.00	15.17	Sandy Loam
90 - 120	0.81	1.40	1.20	70.90	12.00	17.05	Sandy Loam

Results and discussion

As presented in Table 1, the observation sites in each watershed exhibited large variation in soil moisture retention capacity both in space and depth. The average values of moisture retention capacity (Table 1), however, indicated that Arnigad watershed as a whole has higher moisture retention capacity than Bansigad watershed.

For further analysis, monthly soil moisture values were computed from fortnightly field observations at individual sites and depths in both watersheds. The time series data exhibited large variation among the sites as well as along the depth in each watershed. Therefore, mean soil moisture values were computed for analysis of temporal, profile and spatial variation within each

watershed and to compare the soil moisture regimes of two watersheds having different forest cover characteristics.

Table 3. Tree density and dbh of dense and degraded micro-watersheds

Site	Quadrant No.	Arnigad watershed		Bansigad watershed	
		Dbh (cm)	Tree Density (trees·ha^{-1})	Dbh (cm)	Tree Density (trees·ha^{-1})
1	1	32.58	710	9.55	185 (site BA)
	2	24.84	550 (site AA)	14.33	405
	3	28.38	990	9.55	110
	4	26.51	410	22.69	435
	5	24.12	780	11.46	495
2	1	17.07	525	21.5	480
	2	48.83	275 (site AB)	26.91	210 (site BB)
	3	34.71	535	19.27	400
	4	40.66	315	18.59	780
	5	23.14	285	7.96	115
3	1	35.14	320	4.99	335
	2	23.25	630	9.24	310
	3	37.58	460 (site AC)	23.57	615 (site BC)
	4	26.75	310	13.46	425
	5	35.03	430	18.84	590
Average		30.57	502	15.46	392
SD		± 8.22	± 206.67	± 6.63	± 189.58
Percent increase over degraded watershed area		97.74	27.75		

Temporal variation of soil moisture under different forest covers

Temporal variations of spatially averaged monthly soil moisture storage at 25, 50 and 80 cm depths and also monthly rainfall over three years of observation period are plotted in Fig. 4a and 4b for Arnigad and Bansigad watersheds respectively. As can be expected, the soil moisture variation responded well to the rainfall and evapotranspiration with three peaks and three lows over three years of observations. The soil moisture reaches its highest value at all depths during monsoon seasons when most rainfall takes place, though few field observations might not have captured the peaks as the data was recorded at fortnightly intervals.

The soil moisture shows depleting pattern during winters and summers when rainfall is minimal and evapotranspiration is the dominating factor. Also, the soil moisture at 25 cm depth shows a quick response to rainfall while a lag effect is observed at 50 and 80 cm depths. It is obvious that a longer time is required for percolation of water to greater depths (Tyagi et al. 2011). Here, it can be noticed that the shallowest layers in both the watersheds are wetter than other deeper layers even during non monsoon months when evaporation is high. The difference is even more pronounced in case of degraded Bansigad watershed. This is probably due to the fact that even low rainfall amount during winter and summer seasons contribute to shallow layers. Further, low interception losses in degraded forest result in higher amount of rainfall reaching the ground surface (Konstantin et al. 1996), and therefore, the Bansigad watershed shows higher difference in moisture regimes of shallowest layer and deeper layers. In summary, the soil moisture values in both watersheds show an annual cycle. It was also noticed from the data that winter rains of low magnitude and prolonged duration caused rise in soil moisture generally up to 50 cm depth but isolated rainfalls of high magnitude contributed to the soil moisture up to 80 cm depth.

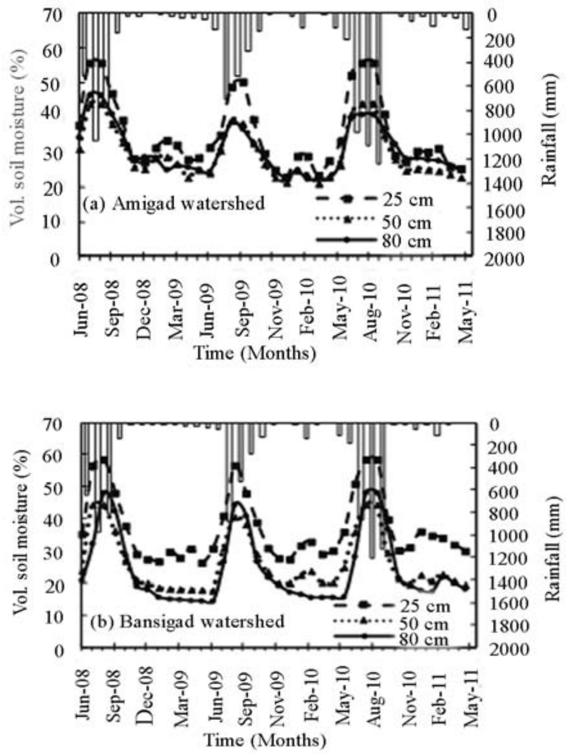

Fig. 4 Temporal variation of soil moisture at different depths in (a) Arnigad, and (b) Bansigad watershed

For analyzing seasonal variation, mean soil moisture was computed for the monsoon (June to September), winter (October to January) and summer (February to May) seasons (Table 4). The highest soil moisture storage is observed during monsoon season which is at 40.33% and 39.34% in Arnigad and Bansigad watersheds respectively. The soil moisture storage in respective watersheds decreases to 29.29% and 25.50% during winter and 25.95% and 22.58% in summer. The reasons for low soil moisture in winter and summer seasons can be explained by the effect of evapotranspiration.

Soil moisture variation along depth

Mean soil moisture values at different depths in Arnigad and Bansigad watersheds (last row of Table 4) are depicted graphically in Fig. 5. In Bansigad watershed, the soil moisture is highest (36.97%) at 25 cm and decreases with increase in depth to 26.22% at 50 cm and to 24.22% at 80 cm. A similar pattern is also observed in Arnigad watershed up to 50 cm depth, but at 80 cm depth the watershed shows slightly higher moisture content than at 50 cm depth. The higher soil moisture content in shallow

layer can be supported by the general notion that organic matter content improves the soil moisture storage capacity of the soil (Larney et al. 1998; Zhao et al. 2006). Hudson (1994) showed that for each 1-percent increase in soil organic matter, the available water holding capacity in the soil increased by 3.7%. Since shallow layers in the study watersheds have higher organic matter content than deeper layers (Table 2), the soil moisture is also higher in shallow layers.

Table 4. Mean soil moisture storage in Arnigad and Bansigad watershed

Variables of mean soil moisture	Soil moisture storage in Arnigad				Soil moisture storage in Bansigad			
	25 cm	50 cm	80 cm	Average	25 cm	50 cm	80 cm	Average
Monsoon season	46.64	37.12	37.24	40.33	48.24	35.59	34.18	39.34
Winter season	30.89	27.40	29.58	29.29	31.93	22.76	21.81	25.50
Summer season	28.56	24.28	25.00	25.95	30.74	20.32	16.66	22.58
Average	35.36	29.60	30.61	31.86	36.97	26.22	24.22	29.14

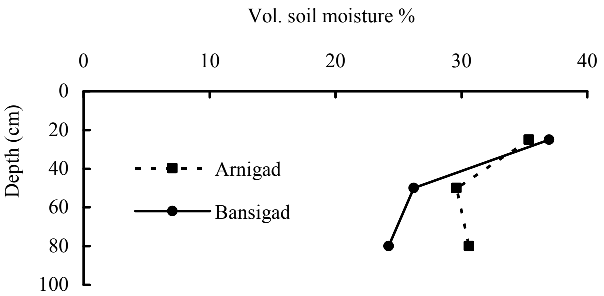

Fig. 5 Soil moisture variation along depth in Arnigad and Bansigad watersheds

The slightly higher moisture storage at 80 cm than at 50 cm depth in Arnigad watershed might have resulted due to either low rate of water movement to soil layer below 80 cm, or high contribution from lateral flow within the soil layer from the upslope because of change in saturated hydraulic conductivity. This can be supported by the observations reported by Venkatesh et al. (2010) in studies conducted elsewhere. A comparison between two forest cover types shows that the soil moisture storage at 25 cm depth is higher in degraded forest than in dense forest. A possible reason for this difference lies in the fact that the site BC (in Bansigad watershed) has a very high storage potential at 25 cm depth (Table 1).

It was reported that the degraded watershed exhibited greater spatial variability in soil moisture; while acacia and forested watersheds, which had comparatively uniform distribution of trees and accordingly uniform utilization of soil moisture, exhibited less spatial variability across all the sites. Topographically, all three sites in each watershed are located almost on the same slope. Therefore, variation in forest cover structure at different sites seems to play a major role in influencing the spatial pattern of soil moisture in the study watersheds. Similar observations were reported by Qiu et al. (2001), Zhou et al. (2001) and Teuling et al. (2006) from the studies conducted elsewhere.

Spatial variation of soil moisture within watersheds

An analysis was carried out to understand how soil moisture storage varies at different sites within each watershed. The change in the mean soil moisture storage at different spatial points in Arnigad and Bansigad watersheds is depicted in Fig. 6a and 6b respectively. It can be observed from Fig. 6 that the soil moisture in Arnigad (dense forest) watershed varies in a narrow range among sites AA (33.80%), AB (29.22%) and AC (32.09%), while a large variation is exihibited by Bansigad (degraded) watershed with soil moisture values as 21.57%, 25.94% and 40.47% at sites BA, BB, and BC, respectively. These results are consistent with the findings reported by Venkatesh et al. (2010).

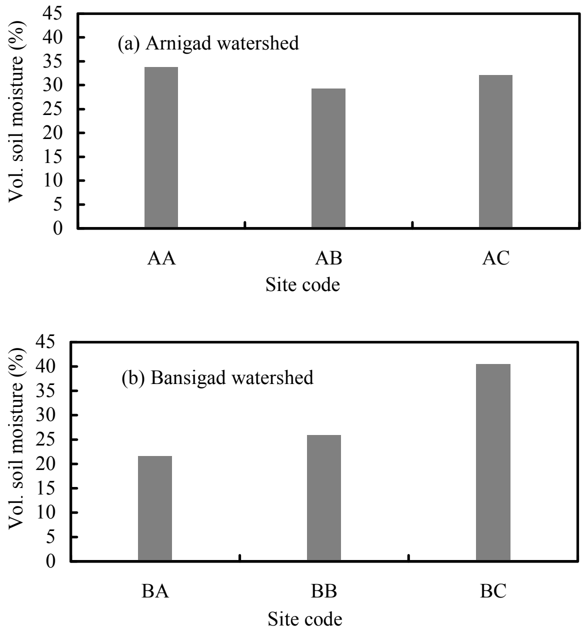

Fig. 6 Variation of soil moisture storage at various sites in (a) Arnigad and (b) Bansigad watersheds

The vegetation survey data (Table 3) shows a tree density of 550, 275, and 460 trees per ha around sites AA, AB, and AC respectively in Arnigad and 185, 210, and 615 trees per hectare around sites BA, BB, and BC respectively in Bansigad watershed. For further analysis, the soil moisture values were plotted against tree density which exhibited a linear relationship with R^2 value of the order of 0.89 (Fig. 7). The analysis clearly shows that the soil moisture storage in the oak forest has a positive correlation with

tree density which is consistent with the findings reported by Sharda and ojaswi (2006). It was reported that root system of an oak tree is very extensive and soil-root complex system of each mature oak tree has a capacity to store several hundred litres of water, which is released as base flow during lean season.

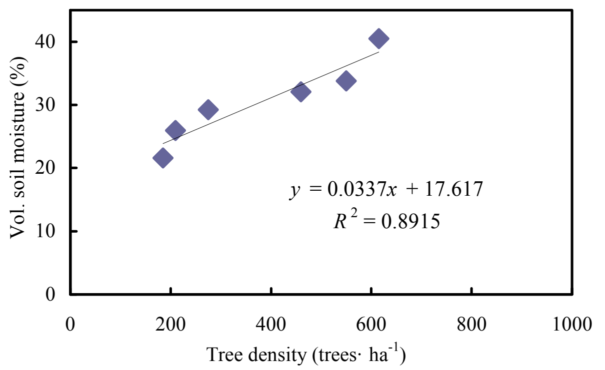

Fig. 7 Relationship between soil moisture storage and tree density

Comparison of soil moisture storage under different types of forest cover

The monthly mean soil moisture values in Arnigad and Bansigad watersheds were plotted (Fig. 8) for overall comparison of soil moisture regime under dense oak and degraded mixed oak forest covers. The peak moisture content in both watersheds corresponds to the heaviest rainfall period. The overall soil moisture regime is found higher under dense forest (Arnigad) than that under degraded forest (Bansigad) except during August when variation in rainfall amounts appears to influence the soil moisture regime in two watersheds. Similar results were reported by Tyagi et al. (2011) in *sal* (shorea robuta) forest in lower Himalayan region of India where highest soil moisture was observed under dense canopy and the soil moisture decreased with decrease in canopy density.

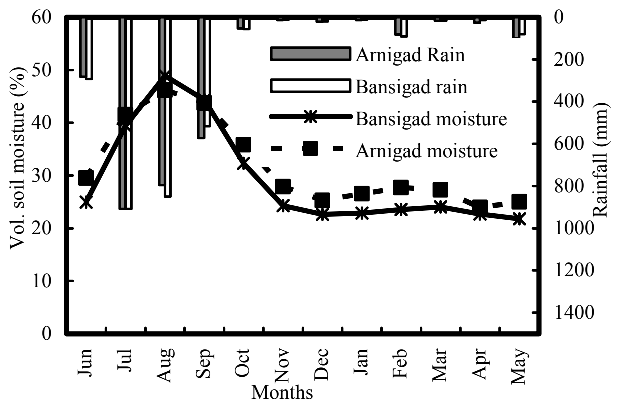

Fig. 8 Comparison of mean soil moisture regime in Dense (Arnigad) and degraded (Bansigad) oak forests

In the present study, the mean soil moisture storage over entire period of study was obtained as 31.86% in Arnigad and 29.14% in Bansigad watershed. The higher soil moisture content in Arnigad watershed could be possibly attributed to (1) higher organic matter content (2) denser roots because of higher tree density, (3) higher infiltration, (4) low evaporation from the soil surface, and (5) higher soil organic carbon content. The organic matter and the root system improve soil structure, increase infiltration of water and water holding capacity of the soil (Marshall and Holmes 1988; Kang et al. 1996; Jiang 1997; Teresaecheverria and Martinez 2001). Dense vegetation cover also intercepts more incoming solar radiation, resulting in less net loss of soil water because of greater reduction in evaporation and smaller increase in vegetation transpiration (Duan et al. 2011). Higher percentage of soil organic carbon, as in the case of Arnigad watershed (Table 2), improves overall soil environment and the soil water holding capacity.

Conclusions

In the present study, soil moisture regime was monitored and analysed in two cover types of oak forest of Arnigad and Bansigad watersheds in lower western Himalayas. The following conclusions were derived from the results of the study.

Soil moisture values in both watersheds show an annual cycle with highs and lows during periods of high rainfall and high evapotranspiration respectively.

The soil moisture storage under dense forest cover was higher than under the degraded forest during all the seasons. The values during monsoon, winter and summer seasons were obtained as 40.33%, 29.29% and 25.95% respectively under dense forest; and 39.34%, 25.50% and 22.58% respectively under degraded forest.

The degraded forest exhibited larger spatial variation in soil moisture than the dense forest which had comparative a uniform distribution of trees across the watershed.

The profile analysis indicated highest soil moisture content at 25 cm depth which decreased with depth in both watersheds.

A high positive correlation was found between tree density and soil moisture content.

The mean soil moisture content, computed over three years of study period, was obtained as 31.86% and 29.14% under dense and degraded forest respectively. These values indicated potential for soil water storage under well managed oak forest and, consequently, for sustainable low flows in Himalayan region.

References

Anderson MG, Kneale PE. 1980. Topography and hillslope soil water relationships in a catchment of low relief. *Journal of Hydrology*, **47**: 115−128.

Andrew WW, Günter B, Rodger BG. 1998. Geostatistical characterisation of soil moisture patterns in the Tarrawarra catchmetn. *Journal of Hydrology*, **205**: 20−37.

Aubert D, Loumagne C, Oudin L. 2003. Sequential assimilation of soil moisture and stream flow data in a conceptual rainfall-runoff model. *Journal of Hydrology*, **280**: 145−161.

Bárdossy A, Lehmann W. 1998. Spatial distribution of soil moisture in a

small catchment Part 1: geostatistical analysis. *Journal of Hydrology*, **206**: 1–15.

Bartarya SK. 1995. Hydrology and water resources of intermontane Doon valley. *Journal of Himalayan Geology*, **6**(2): 17–28.

Bell KR, Blanchard BJ, Schmugge TJ, Witczak MW. 1980. Analysis of surface moisture variations within large field sites. *Water Resources Research*, **16**(4): 796–810.

Duan L, Liu T, Wang X, Wang G, Ma L, Luo Y. 2011, Spatio-temporal variations in soil moisture and physicochemical properties of a typical semiarid sand-meadow-desert landscape as influenced by land use. *Hydrol Earth Syst Sci*, **15**: 1865–1877.

Famiglietti JS, Rudnicki JW, Rodell M. 1998. Variability in surface soil content along a hillslope transect: Rattlesnake Hill, Texas. *Journal of Hydrology*, **210**: 259–281.

Fu B, Chen L. 2000. Agricultural landscape spatial pattern analysis in the semi-arid hill area of the Loess Plateau, China. *Journal of Arid Environments*, **44**(3): 291–303.

Fu B, Wang J, Chen L, Qiu Y. 2003. The effect of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. *Catena*, **54:** 197–213.

Hudson BD. 1994. Soil organic matter and available water capacity. *J Soil Waert Conserv*, **49**(2): 189–194.

Jiang D. 1997. *Soil Erosion and Control Models in the Loess Plateau*. Beijing: Water Resources Press, p. 33. (in Chinese).

Kang S, Zhang S, Nie G, Shi S, Gou Z, Qi Z, Cui X. 1996. Research on soil infiltration distribution of Aobao water basin in Inner Mongolia. *Journal of Soil Erosion and Soil and Water Conservation*, **2**(2): 38–46.

Konstantin Y. 1996. Scales of temporal and spatial variability of mid latitude soil moisture. *Journal of geophysical research*, **101**(D3): 7163–7171.

Larney F, Bullock M, Janzen H, Ellert B, Olson ECS. 1998. Wind erosion effects on nutrient redistribution and soil productivity. *J Soil Water Conserv*, **53**: 133–140.

Mahmood R, Hubbard KG. 2007. Relationship between soil moisture of near surface and multiple depths of the root zone under heterogeneous land uses and varying hydro climatic condition. *Hydrological Processes*, **21**: 3449–3462.

Marshall T J, Holmes J W. 1988. *Soil Physics* (2nd edition). Cambridge: Cambridge University Press, p. 89–220.

Moore ID, Burch GJ, Mackenzie DH. 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. *Transactions of the American Society of Agriculture Engineering,* **31**: 1098–1107.

Qiu Y, Fu B, Wang J, Chen L. 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the loess plateau, China. *Journal of Hydrology*, **240**: 243–263.

Rautela P, Joshi G C, Bhaisora B. 2010. Seismic vulnerability and risk in the Himalayan township of Mussoorie, Uttarakhand, India. *Current science*, **99**(4)**:**521–526.

Sharda VN, Ojaswi PR. 2006. Hydrological evaluation of forest tree covers in different agro-ecological regions of India. In: *Proc. Int. Workshop on Impacts of Reforestation of Degraded Lands on Landscape hydrology in the Asian Region,* Roorkee, India. 6–10 March, pp. 1–18.

Teresaecheverria P, Martinez J. 2001. Soil moisture in oak-wood and pine wood of the moncayo (Ibrerian range, spain). *Cuadernos de Investigacion Geografica,* (27): 17–26, ISSN 0211–6820.

Teuling AJ, Uijlenhoet R, Hupet F, Van Loon EE, Troch PA. 2006. Estimating spatial mean root zone moisture from point scale observations. *Hydrology Earth System Science*, **10**: 755–767.

Thakur V C, Pandey A K. 2004. Late Quaternary tectonic evolution of Dun in fault bend/propagated fold system, Garhwal Sub-Himalaya. *Current Science*, **87** (11): 1567–1576.

Tyagi JV, Kumar R, Srivastava SL, Singh RD. 2011. Effect of micro-environmental factors on natural regeneration of *Sal* (S*horea robusta*). *Journal of Forestry Research*, **22**(4): 543–550.

Venkatesh B, Lakshman N, Purandra BK, Reddy VB. 2010. Analysis of observed soil moisture patterns under different land covers in Western Ghats, India. *Journal of hydrology*, **397**(3–4): 281–294.

Venkatesh B, Nandagiri N, Purandara BK, Reddy BV. 2011. Modelling soil moisture under different land covers in a sub-humid environment of Western Ghats, India. *J Earth Syst Sci*, **120**(3): 387–398.

Western AW, Grayson RB, Bloschl G, Willgoose GR, McMohan TA. 1999. Observed spatial organization of soil moisture and its relation to terrain indices. *Water Resources Research*, **35**(3): 797–810.

Wilson DJ, Western AW, Grayson RB. 2005. A terrain and data based method for generating the spatial distribution of soil moisture. *Advances in Water Resources*, **28**: 43–54.

Zhao HL, Yi XY, Zhou RL, Zhao XY, Zhang TH, Drake S. 2006. Wind erosion and sand accumulation effects on soil properties in Horqin Sandy Farmland, Inner Mongolia. *CATENA*, **65**: 71–79.

Zhao XG, Wu FG, Liu BZ, Liu SH. 1999. Effects of primary factors on soil moisture in cultivated slopeland on loess plateau. *Bulletin of Soil and Water Conservation*, **19**(1): 10–14, (in Chinese).

Zhou GY, Morris JD, Yan JH, Yu ZY, Peng SL. 2001. Hydrological impacts of reforestation with eucalyptus and indigenous species: a case study in Southern China. *Forest Ecology and Management*, **167**(1–3): 209–222.